Research Statement

Research accomplishments

Overview. My research has focused on understanding the impact of flow physics on the biological and ecological functions of cilia and ciliated systems. Using both analytical and computational methods, I develop mathematical models to describe ciliary motion in single-cell eukaryotes and analyze how interactions between cilia and the surrounding fluid dictate their feeding performance and surrounding nutrient transport. Through this lens, I systematically analyze the functional design of single cells, specifically how the coordination between feeding apparatuses and ciliary arrangements enhances feeding efficiency. Driven by a curiosity for cell development, I am now seeking a postdoctoral position that will allow me to explore more dynamics in cellular research.

Comparative Study of Nutrient Acquisition Strategies in Single-cell Cilites. Nutrient acquisition is crucial and challenging for oceanic microbes due the patchy distribution of nutrient particulates within oceanic environments. Some oceanic protists enhance their feeding rates by coordinating the motion of their hair-like appendages, such as cilia and flagella. These protists face an evolutionary dilemma: whether to actively swim towards nutrient-rich regions or to attach themselves to substrates and create feeding currents to capture prey. Both "swim" and "stay" strategies are observed in different species within natural communities, with previous studies suggesting each strategy as an optimal nutritional approach. To address this debate from a fluid dynamics perspective, I explore the following questions: **(Q1)** What are the flow features around sessile ciliates compared to motile ciliates? **(Q2)** How does cilia-driven flow affect the nutrient transport and, consequently, the feeding rate of ciliated microorganisms? Is mobility a crucial factor? **(Q3)** In addition, ciliates exhibit considerable variation in the morphology of their feeding apparatus and ciliary arrangement. Can flow physics reveal the functional design principles behind these variations?

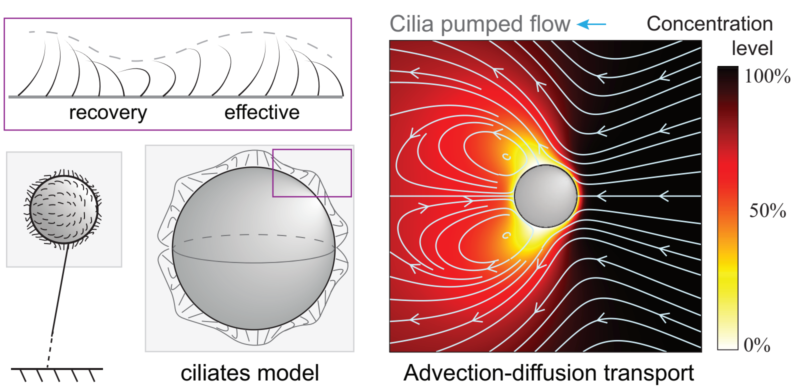

Figure 1: **Model sessile ciliates.** Streamlines (arrow lines) of surrounding fluid flow and the corresponding nutrient concentration field (colormap) by advection-diffusion transport.

(Q1) I developed a mathematical model for sessile ciliated microorganisms based on the classic Blake's envelope model, treating the organism in a spherical shape with periodic surface velocity (see Fig.1). The surrounding flow field is derived analytically by solving the Stokes equation and analyzed through spherical harmonics decomposition. **(Q2)** The nutrient concentration field around the organism is modeled using an advection-diffusion equation, and the feeding rate was estimated by Fick's law. Through analytical analysis and numerical computations, I explored ciliates' feeding behavior under extreme Péclet numbers to identify the optimal cilia-driven surface motion that maximizes feeding rates. This result is consistently confirmed by a backward PDE-constrained optimization problem using the adjoint-based method [1]. To confirm the model prediction with biological observation, I conducted a comprehensive review of biological data to validate model predictions against real ciliate shapes and flow data. Notably, I found that at high Péclet numbers, feeding rates for both motile and sessile ciliates become asymptotically equivalent, providing insights into the optimal nutrient acquisition strategy [2]. **(Q3)** Through a systematic study of various cilia configurations and feeding apparatus designs in model ciliates, I discovered that the optimal design for sessile ciliates is a ciliary ring, while motile ciliates benefit from ciliary coverage over the entire non-oral region. Interestingly, this finding on extracellular transport function design of cells, bridging by phagocytosis, matches the intracellular transport mechanisms design that we observed in nature [3].

Modeling ciliary fluid flow in spherical confinement The study of cilia-driven flow extends beyond ciliated microorganisms, playing a crucial role in understanding embryo development, where the emergence of asymmetry is closely linked to the subsequent formation of asymmetric organs and morphological structures. Symmetry-breaking events, facilitated by ciliary-directed fluid flow, are observed across various species, including mice, Xenopus, zebrafish, among others.

My interest lies in understanding cilia function in the formation of directional flow and investigating the robustness of flow patterns generated during biological development, where stochastic processes are inherent. Among the diverse morphologies observed in these systems, I am particularly interested in fluid flow within closed confinement. To explore this, I considered a mathematical model that treats each cilium as a point force, simulating the fluid flow driven by randomly distributed point forces within a closed spherical confinement (see Fig.2). In this project, I conducted probability analysis, both numerically and analytically, to examine the flow generated by randomly distributed cilia. Currently, I am pursuing a deeper study of this topic.

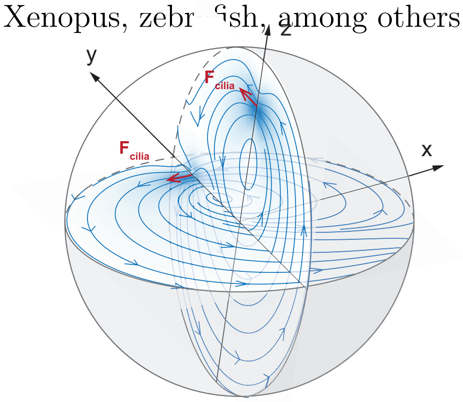

Figure 2: **Model ciliary flow** in a closed spherical confinement.

Research interests and future plan

To expand my research scope, I am interested in exploring more biological problems affected by microhydrodynamics, which reveal phenomena that differ from conventional fluid dynamics in large-scale systems that we seen in everyday scenarios. In particular, my initial exploration into cytoplasmic flow and embryo development using a simple model has triggered my interest in investigating the robust processes of embryonic development, despite the inherent stochasticity. Although stochastic processes are embedded in natural systems, biological development remains robust from a statistical perspective. I am motivated to explore time-evolving dynamics in biology and to investigate how evolutionary robustness integrates with inherent randomness. On a broader scale, this curiosity drives me to delve into emergent phenomena within living systems, with the aim of understanding the underlying dynamics and fundamental physics that govern these processes.

While applying my theoretical and computational analysis experience in fluid dynamics, I seek to further develop my quantitative analysis skills in numerical computation, and I am willing to explore new research techniques. Through computational studies and analytical approaches, I aim to discover more patterns in diverse natural systems and to deepen our understanding of the fundamental physics driving their dynamics, ultimately contributing to a broader understanding of natural phenomena.

References

[1] Jingyi Liu, Yi Man, John H Costello, and Eva Kanso. Optimal feeding of swimming and attached ciliates. https://arxiv.org/abs/2404.13467, 2024.

[2] Jingyi Liu, Yi Man, John H Costello, and Eva Kanso. Feeding rates in sessile versus motile ciliates are hydrodynamically equivalent. https://elifesciences.org/reviewed-preprints/99003, 2024.

[3] Jingyi Liu, John H Costello, and Eva Kanso. Flow physics of nutrient transport drives functional design of ciliates. (submitted).